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# Feasibility Study on Producing Domestic Biofuels from Agricultural Biomass in Japan

UEDA Tatsuki*

Contents

## I　Introduction

Following recent increases in energy demands from large emerging economies, it is now widely recognized that the current global trends in energy supply and consumption are unsustainable, both economically and environmentally (IEA, 2008). Mankind is thus facing a major challenge of developing a low-carbon, environmentally-friendly, yet reliable and affordable, system of energy supply.

Bioenergy could contribute to this challenge because of its renewable and low-carbon nature. In particular, global production of liquid biofuels is significantly increasing in recent years. It had tripled between 2002 and 2005, to attain around 38 billion L of bioethanol mainly in Brazil, USA and China, and over 3 billion L of biodiesel mostly in Europe (OECD/IEA, 2007).

On the other hand, the world is increasingly aware of negative impacts of biofuel productions on world agriculture and food security (FAO, 2008). This is because the world energy markets are far bigger than the food markets, and therefore the increasing demand for energy crops (feedstock) could potentially overwhelm the demand for food crops. For instance, sharp increases in global food prices in 2008 were partly attributed to the increases in biofuel productions (FAO, 2008). Besides, growing feedstock productions have provoked widespread concerns for associated land-use changes (i.e. conversions of natural lands into farmlands), and subsequent negative impacts on land and water resources and biodiversity (FAO, 2008). For instance, it has been criticized that biofuel productions caused, either directly or indirectly, conversions of natural rainforests into energy crop plantations in some tropical countries.

The above backgrounds would give rationale for investigating into the possibilities of producing domestic biofuels in Japan for three reasons. First, farmland resources in rural Japan are now underutilized: around 0.38 million ha of

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* Laboratory of Farmland Engineering, Department of Land and Water Resources

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farmlands (or about 10％ of the total) remained fallow or abandoned (Census of Agriculture and Forestry 2005 (MAFF, 2010)). Such farmlands could be employed for energy crop cultivation without changing current food production potential. In addition, most of agricultural and forestry residues remains underutilized at present. Therefore, biofuels could be produced at a large scale in Japan without causing much land-use change. Second, Japan depends heavily on imported fossil resources to drive its economy, and hence struggles to increase the energy self-sufficiency. Japan's energy mix in 2003 was 50％ of oil, 20％ of coal, 14％ of natural gas and 9％ of nuclear energy (METI, 2006), and virtually all of the raw materials were imported from abroad. The Japanese government therefore envisages increasing its energy self-sufficiency by promoting renewable energies which could be supplied domestically. Third, under the Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC), Japan is obliged to cut greenhouse gas emission by 6％ compared to the 1990 level. Although every sector in Japan is now struggling to reduce its part of emissions, additional countermeasures are awaited in order to meet the goal of the Kyoto Protocol.

As one of the possible solutions to meet these challenges, biofuel production has been paid increasing attentions in recent years. Accordingly, in February 2007, the Japanese Government established a plan to expand domestic biofuel production, with a goal of replacing 10％ of Japan's gasoline consumption (roughly equivalent to 6 million kL/year of bioethanol) by 2030, by employing domestic energy crops as well as agricultural and forestry residues (MAFF, 2007).

In order to formulate detailed plans to achieve such a goal, quantitative analyses and discussions based on actual circumstances surrounding Japanese agriculture are essential. However, whereas a number of studies have evaluated energy balances and costs of biofuels in USA and Europe (e.g. Hill et al., 2006; Hammerschlag, 2006; Shapouri et al., 2002; Pimentel and Patzek, 2005; ETSU, 1996), such studies are still few in Japan. For instance, Saga et al. (2008; 2010) demonstrated that a positive energy balance could be achieved in bioethanol and electricity productions from rice straw. Yanagida et al. (2010) conducted detailed cost analyses on bioethanol using rice straw, and found the costs depended on various process efficiencies. Although their studies provided useful information, the analyses were limited to bioethanol from rice straw. By contrast, Ueda (2006; 2008) conducted life cycle assessment (LCA) on energy balance and greenhouse gas emission, as well as cost analysis, on several potential energy crops and rice straw produced in Japan, but his arguments were sometimes based on rather ideal assumptions on crop yields as well as the conversion efficiency of ligno-cellulosic bioethanol.

The present study therefore aims at investigating the feasibilities and potentials of producing biofuels from several sorts of agricultural biomass in Japan by following the approach of Ueda (2008), but employing more realistic statistics and data as far as possible. Following Ueda (2008), analyses are focused on energy balance, greenhouse gas emission and production cost. These factors are selected because any biofuel production should at least produce positive energy and reduce some greenhouse gas: otherwise it may end up in wasting, rather than saving, fossil fuels, and degrading the environment. Moreover, economic viability also matters for actually disseminating biofuels, although simple cost analyses may often ignore such externalities as enhancement of rural employment and conservation of farmland resources, which are important issues in Japan. It should be noted that, although the author tries his best to collect realistic, actually demonstrated data as far as possible, some calculations still have to be done on various assumptions, as commercial-scale biofuel productions are yet to be materialized in Japan so far.

## II Life cycle assessment (LCA)

### 1 Methodology

### a Scope of study

**Fig.1** shows feedstock for biofuel production, which comprises several energy crops and rice straw, with associated conversion technologies and bioenergies, which are examined in this study. (Sorghum and rice straw are classified here as ligno-cellulosic biomass.) All the crops in **Fig.1**, including ones for tropical, temperate and cold climates, are currently cultivated somewhere in Japan for food or animal feed, thanks to an extensive geographical range of the Japanese archipelago. It is assumed that all the energy crops are cultivated on dedicated farmlands (mainly fallow lands), while rice straw is collected at ordinary paddy fields which regularly produce rice for food.

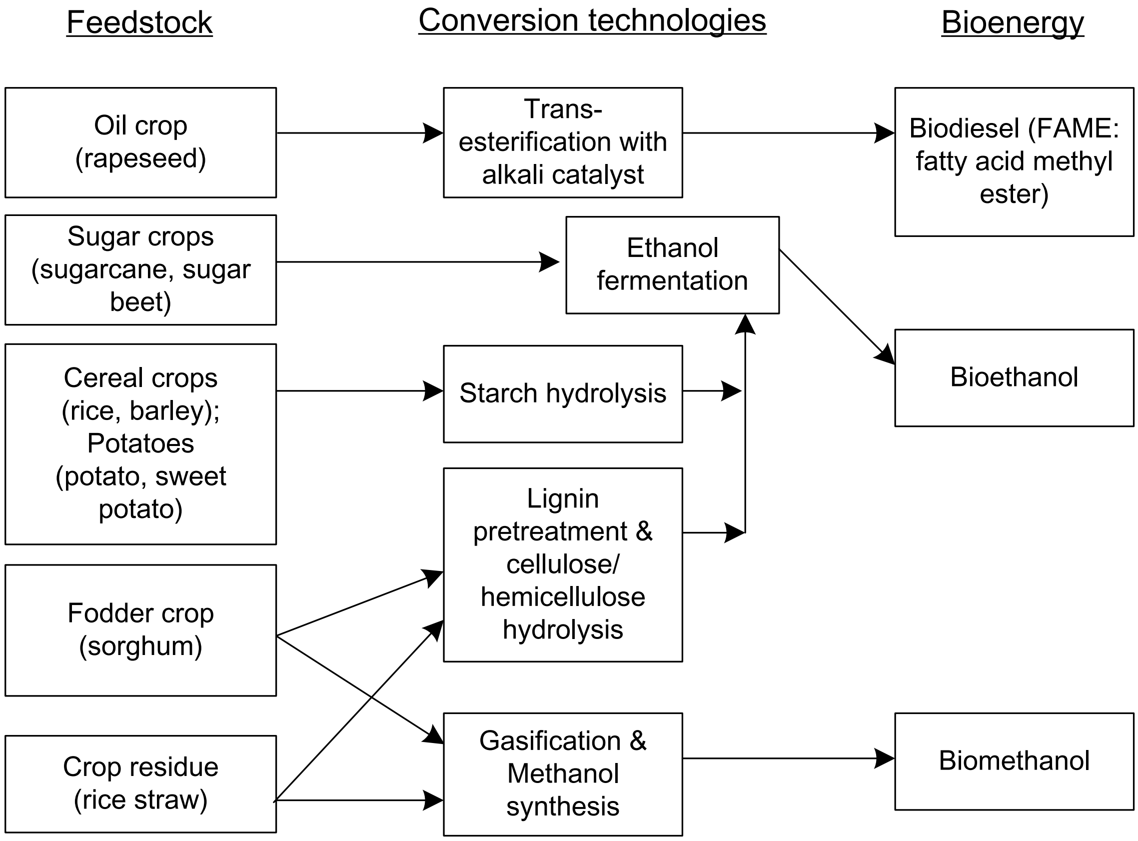

**Fig.1** Feedstock, conversion technologies and bioenergy examined in this study

### b Functional units

The functional unit of the LCA is “1 GJ of bioenergy produced”. However, within the crop production inventory (mentioned below), the functional unit is set as “crop production on 1 ha of farmland”.

### c System boundary and allocation

The system boundary of the LCA is cultivation of energy crops; their transportation from farms to conversion facilities; conversion from crops to biofuels; and transportation of biofuels to fuel-supply stations. Exceptionally, a boundary of the “rice straw” inventory only includes collection of straw on farms, its transportation, and application of chemical fertilizer that compensates the nutrient removed with the straw (Ohta, 2007; Ueda et al., 2007), but excludes cultivation of rice itself. (It should be noted, however, preparation of rice straw in this way may later be referred to as “cultivation” alongside the other crops to simplify the terms.) Such an approach to system boundary is similar to a previous study on corn stover ethanol (Sheehan et al., 2004).

Within these boundaries, two life cycle inventories (LCI) are created and interconnected: i.e. “crop production” and “energy conversion” LCIs, both of which also include relevant transportation phases (**Fig.2**). Production of bioenergy could simultaneously produce various byproducts, such as process residues and wastewater. In this study, however, energy consumption or greenhouse gas emission is not allocated to these byproducts, because the demands for them have not been well established in Japan so far.

### d Data collection

Ueda (2008) earlier compiled the above-mentioned two LCIs, which is basically followed in this study. Nevertheless, this study updates the information on the following points:

1. The yields of energy crops are drawn from the statistical database of the Ministry of Agriculture, Forestry and Fisheries of Japan, instead of those of experimental stations. This would make the analytical results more representative of ordinary farmlands across Japan.
2. Some data on inputs for crop cultivation are updated after Shimizu et al. (2009).

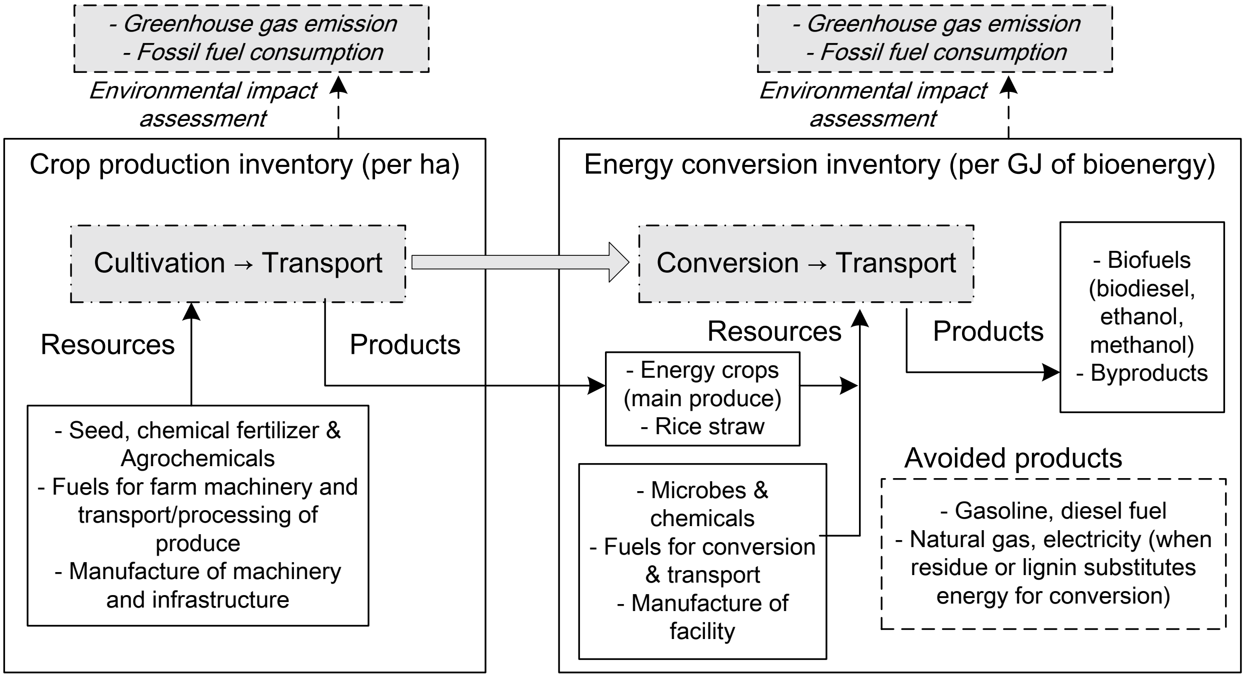

**Fig.2** Outline of the life cycle inventory

3. Some data regarding ethanol production from rice straw are updated after JARUS (2010).
4. Assumptions for the two scenarios (explained in Section II-1-e below) were simplified.

Outlines of the LCIs and LCI analyses for this study, including the above points, are described below. For further details, Ueda (2008) should be consulted.

### (1) Data on crop production

Data on yields of energy crops are collected from the statistical database of the Ministry of Agriculture, Forestry and Fisheries of Japan (MAFF, 2010). The analyses are therefore confined to the crops for which such data are provided (**Table 1**). **Table 1** shows the average yields of all regions where the relevant crops are cultivated, and of the last 5 years in which statistics are available. The yield of rice straw is assumed to be 80% of the amount produced at ordinary paddy fields (**Table 1**), as 80% of them is not positively utilized at present (MAFF, 2005).

Data on fuel inputs for crop cultivation are mainly drawn from Shimizu et al. (2009). Data on chemical fertilizer inputs are collected from reports of experimental stations across Japan, as the LCA needs quantitative data based on the ingredients (e.g. nitrogen and phosphorous). Those stations usually follow standard amounts of fertilizer inputs when they test their varieties. Data on other inputs for crop cultivation (e.g. seeds and agrochemicals) and crop processing were supplemented by NIAES (2003) and other sources.

As for the manufacture and maintenance of agricultural machinery, irrigation facilities and agricultural buildings, it is assumed that these operations consume a sum of 1538 MJ of primary energy per 1 ha of farmland per year (Hill et al., 2006) for each crop. This is a rather simplified assumption neglecting complex nature of Japanese agricultural systems. (For instance, it is not simple to allocate energy consumption for building and maintaining irrigation canals, which may be used for both food and biofuel productions.) However, as energy crop production has not been widespread in Japan, detailed analyses on this issue will be left to future studies.

Regarding greenhouse gas emission from farmland soils, it is assumed that nitrous oxide ($N_2O$) gas is emitted at 0.029kg (from upland field) or 0.024kg (from paddy field), when 1 kg-N of nitrogen fertilizer is applied onto the farm (MOE, 2003). In addition, 32 kg/ha of methane gas is thought to be emitted in paddy fields (MOE, 2003; IPCC, 1996), which applies to a case of rice production only.

**Table 1** Main data on crop production and energy conversion efficiency

| | Unit | Rapeseed | Sugarcane | Sugar beet | Rice | Barley | Potato | Sweet potato | Sorghum | Rice straw |
|---|---|---|---|---|---|---|---|---|---|---|
| Biofuels [a] | | BDF | ET (sugar) | | ET (starch) | | | | ET (ligno-cellulosic) / MT | |
| **Products (Outputs) and efficiencies** | | | | | | | | | | |
| Crop yield [b] | t/ha | 2.1 | 61.7 | 63.6 | 5.2 | 3.1 | 44.4 | 24.7 | 15.3 | 4.2 |
| Oil/sugar/starch content | % | 45.8 | 15.0 | 17.7 | 73.8 | 76.2 | 22.5 | 29.1 | − | − |
| Biofuel yield [c] | % | 90.0 | 79.9 | 79.9 | 81.0 | 81.0 | 86.1 | 86.1 | − | − |
| Gross biofuel production per feedstock [d] | L/t | 472 | 78.0 | 92 | 430 | 444 | 139 | 180 | 145<br>(565) | 145<br>(488) |
| Gross biofuel production per farmland [d] | kL/ha | 0.98 | 4.78 | 5.82 | 2.25 | 1.36 | 6.19 | 4.46 | 2.21<br>(8.63) | 0.61<br>(2.06) |
| **Resources (Inputs)** | | | | | | | | | | |
| Ammonium nitrate (as N) | kg/ha | 100 | 162 | 116 | 120 | 150 | 120 | 36 | 320 | 21 |
| Phosphate (as $P_2O_5$) | kg/ha | 160 | 120 | 248 | 90 | 90 | 200 | 48 | 200 | 12 |
| Potassium (as $K_2O$) | kg/ha | 100 | 150 | 140 | 131 | 150 | 150 | 72 | 320 | 87 |
| Magnesium | kg/ha | − | − | 50 | − | − | 35 | − | − | − |
| Lime | kg/ha | − | − | − | − | − | − | − | 1000 | − |
| Silica | kg/ha | − | − | − | − | − | − | − | − | 267 |
| Agrochemicals | kg/ha | 1 | 58 | 16 | 22 | 15 | 7 | 2 | − | − |
| Seed | kg/ha | 6 | − | 1 | 35 | 100 | − | − | 20 | − |
| Gasoline (for cultivation) | MJ/ha | − | − | 45 | 840 | 62 | − | 333 | 2135 | − |
| Diesel (for cultivation) | MJ/ha | 4259 | 16376 | 9577 | 1368 | 3469 | 7166 | 3961 | 7839 | 1203 |
| Electricity (for cultivation & drying) | kWh/ha | − | − | − | 17 | 279 | − | − | 9 | − |
| Diesel (for drying) | MJ/ha | 2422 | − | − | 5956 | 7088 | − | − | − | − |

**Notes**:

[a] BDF: biodiesel fuel, ET: bioethanol, MT: biomethanol.

[b] Air-dry weight for oil and cereal crops; oven-dry weight for sorghum and rice straw; wet weight for other crops.

[c] Ratio to the theoretical yield: i.e. from 100g of oil to c.a. 100g of biodiesel; from 100g of glucose to 51.14g of bioethanol.

[d] Calculated on the basis of biomass weights stated in Note (b). As for ligno-cellulosic biomass, figures in the upper row indicate the yields of bioethanol, while those in the lower row (in parentheses) those of biomethanol.

**Main data sources** (for more details, see text and Ueda (2008)):

－Crop yield: MAFF (2010): [Energy crops] national average of the last 5 years; [Rice straw] 80％ of the amount generated at ordinary paddy fields.

－Biofuel yield & Gross biofuel productions: [Biodiesel] JIE (2002); [Bioethanol from sugar crops and potatos] Daisho et al. (2004); [Bioethanol from cereal crops] NFACA (2006); [Ligno-cellulosic bioethanol] JARUS (2010); [Biomethanol] NEDO (2001).

－Oil/sugar/starch content & Fertilizer inputs: [Rapeseed] Aomori Pref. (2001) and Okuyama et al. (1994); [Sugarcane] Ujihara et al. (2002); [Sugar beet] Kawakatsu et al. (1991); [Rice] Uehara et al. (2003) and MEXT (2005); [Barley] Shikoku region naked barley research group (2003) and MEXT (2005); [Potato] Asama et al. (1982); [Sweet potato] Kumagai et al. (2002); [Sorghum] Nakagawa et al. (1995); [Rice straw] Ohta (2007).

－Other inputs: Shimizu et al. (2009); NIAES (2003); TSK (2005); MAFF (1965-72).

### (2) Data on energy conversion and transportation

Data on energy conversion of biomass (**Tables 1** and **2**) are obtained from publications in Japan and the United States (Daisho et al., 2004; Hill et al., 2006; JIE, 2002; NEDO, 2001; 2006; NFACA, 2006; JARUS, 2010).

Among the collected data, those of conversion efficiencies for ligno-cellulosic bioethanol remain most controversial as the technology has not been fully mature yet. This study follows recent data from a pilot experiment in Japan (JARUS, 2010). Their experiment was conducted at a scale of 300L/year, using rice straw as raw material and hydrothermal-enzymatic processes for hydrolysis. They consequently achieved a conversion efficiency of 145(L-ethanol/odt (oven dry ton)-feed) on average, which is adopted for the current analysis. The conversion efficiency for sorghum is assumed to be the same as this data.

Fossil energy requirement for energy conversion processes has also caused much controversy. This study adopts an average energy requirement (referred to as $ER_{corn} = 625$ MJ/GJ-ethanol) (**Table 2**) after Hammerschlag (2006), who reviewed six representative studies on corn bioethanol in the United States. Bioethanol conversion from other starch crops is thought to consume the same amount of energy as $ER_{corn}$. As bioethanol conversion from sugar crops does not require the starch hydrolysis process (**Fig.1**), energy required for that process (25％ of the total) is subtracted from $ER_{corn}$ (**Table 2**). As for ligno-cellulosic bioethanol, energy for producing chemicals for lignin pretreatment and hydrolysis (NEDO, 2006) is added to $ER_{corn}$ (**Table 2**). It should be noted, however, the total energy requirement for producing ligno-cellulosic bioethanol still remains uncertain, as it depends on the hydrolysis process applied, the conversion efficiency and the scale of production.

Manufacture and maintenance of a conversion facility is thought to consume a total of 2 MJ of primary energy per 1 GJ of biofuel produced (Hill et al., 2006). Although this is a rather simplified assumption, detailed analyses on this point may well be left until commercial-scale conversion plants are actually built in Japan.

Regarding transportation, the author assumes that agricultural produce is transported from farms to conversion plants on a 43-km trip (TSK, 2005), while biofuels from plants to fuel-supply stations on a 209-km trip (CNRE, 2006).

### e Scenarios

This study compares two kinds of scenarios, namely “Scenario 1 (fossil-fuel based systems)” and “Scenario 2 (bioenergy based systems)” (**Table 2**), which are explained below. Both scenarios commonly assume that fossil fuels provide necessary fuel energy in crop production/processing and transport phases.

### (1) Scenario 1 (fossil-fuel based systems)

Scenario 1 simply assumes to depend on fossil fuels alone (natural gas and grid electricity) to drive energy conversion processes (**Table 2**), including wastewater treatment processes. There would be no recycling of wastewater or residues to farmlands.

### (2) Scenario 2 (bioenergy based systems)

Scenario 2 sets a primary objective on saving fossil energy inputs. It therefore assumes to employ crop residues, lignin, or biomass co-generation (explained below) to replace fossil fuels as far as possible. In addition, in bioethanol production, wastewater from fermentation process is directly applied to farmlands, thereby halving nitrogen and potassium fertilizer inputs, and cutting energy input for drying/treating the wastewater. Details of the assumptions are discussed below.

Firstly, we discuss a possibility of using crop residues for providing energy for conversion. To begin with, using harvest residues (such as leaves and stalks) for this purpose would face a potential problem of depleting soil nutrition provided by them. Under the assumed crop yields, generated amounts of harvest residues from each crop are actually smaller than the required amounts that should be left on fields for controlling erosion and soil nutrition, which is assumed to be 4.91 (odt (oven dry ton)/ha) after Sheehan et al. (2004). Besides, collecting and transporting harvest residues to a conversion facility would entail additional costs. Therefore, this study does not consider the use of harvest residues for providing heat for conversion.

On the other hand, process residues, such as rice/barley husks, bagasse (solid residue of sugarcane), lignin, and other fibrous matters contained in the produce, would be easier to recover and use. In fact, bagasse and lignin are widely utilized for providing energy at bioethanol plants in Brazil as well as sugar refineries and paper mills across the world. By contrast, residues from sugar beet, potato and sweet potato are so moist and degradable that they are not

**Table 2** Outline of the scenarios in LCA

| | Rapeseed | Sugarcane | Sugar beet | Rice | Barley | Potato | Sweet potato | Sorghum | Rice straw | Sorghum | Rice straw |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Biofuels[a] | BDF | ET (sugar) | | ET (starch) | | | | ET (ligno-cellulosic) | | MT | |
| **Scenario 1 (fossil-fuel based systems)** | | | | | | | | | | | |
| Crop production | | | | | | | | | | | |
| Chemical fertilizer[b] | ST | ST | ST | ST | ST | ST | ST | ST | ST | ST | ST |
| Wastewater application to farm | − | No | No | No | No | No | No | No | No | − | − |
| Energy sources for hydrolysis, fermentation, distillation & wastewater treatment | | | | | | | | | | | |
| Fossil fuels | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Available energy from residues (MJ/GJ-fuel) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Energy consumptions in conversion processes (MJ/GJ-fuel) | | | | | | | | | | | |
| Total | 245 | 469 | 469 | 625 | 625 | 625 | 625 | 684 | 684 | 421 | 421 |
| Hydrolysis | − | 0 | 0 | 156 | 156 | 156 | 156 | 156 | 156 | − | − |
| Fermentation & distillation | − | 262 | 262 | 262 | 262 | 262 | 262 | 262 | 262 | − | − |
| Wastewater treatment | − | 207 | 207 | 207 | 207 | 207 | 207 | 207 | 207 | − | − |
| Wastewater transport to farms | − | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | − | − |
| Chemicals for pretreatment | − | − | − | − | − | − | − | 59 | 59 | − | − |
| **Scenario 2 (bioenergy based systems)** | | | | | | | | | | | |
| Crop production | | | | | | | | | | | |
| Chemical fertilizer[b] | ST | R | R | R | R | R | R | R | R | ST | ST |
| Wastewater application to farm | − | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | − | − |
| Energy sources for hydrolysis, fermentation & distillation | | | | | | | | | | | |
| Fossil fuels | | | ○ | ○ | ○ | ○ | ○ | | | | |
| Process residue (Lignin) | | | | | | | | ○ | ○ | | |
| Process residue (Others) | ○ | ○ | | ○ | ○ | | | | | | |
| Biomass co-generation | | | | | | | | | | ○ | ○ |
| Available energy from residues or biomass co-generation (MJ/GJ-fuel) | 270 | 667 | 0 | 196 | 263 | 0 | 0 | 552 | 960 | 421 | 421 |
| Energy consumptions in conversion processes (MJ/GJ-fuel) | | | | | | | | | | | |
| Total | 245 | 360 | 360 | 516 | 516 | 516 | 516 | 575 | 575 | 421 | 421 |
| Hydrolysis | − | 0 | 0 | 156 | 156 | 156 | 156 | 156 | 156 | − | − |
| Fermentation & distillation | − | 262 | 262 | 262 | 262 | 262 | 262 | 262 | 262 | − | − |
| Wastewater treatment | − | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | − | − |
| Wastewater transport to farms | − | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | − | − |
| Chemicals for pretreatment | − | − | − | − | − | − | − | 59 | 59 | − | − |

**Notes**:

[a] BDF: biodiesel fuel, ET: bioethanol, MT: biomethanol.

[b] ST (standard amount): the amount stated in Table 1. R (reduced amount): 50％ of standard amount for nitrogen and potassium fertilizers, and 100％ for other fertilizers.

**Main data sources** (for more details, see text and Ueda (2008)):

−Energy consumptions in conversion processes: [Biodiesel] Hill et al. (2006); [Sugar/starch bioethanol] Hammerschkag (2006); [Ligno-cellulosic bioethanol] NEDO (2006); [Biomethanol] NEDO (2001).

suitable for energy recovery by combustion, and therefore excluded from further analyses.(Nevertheless, energy could still be recovered from those residues using methane fermentation. Analyses on such possibilities are left to future studies.) **Table 2** (Scenario 2) shows the available amounts of the other process residues, which would be generated alongside the production of 1 GJ of biofuels. Rapeseed, sugarcane, and sorghum and rice straw (for bioethanol) have enough residues to meet direct energy demands of conversion processes (i.e. hydrolysis, fermentation and distillation) (**Table 2**). Accordingly, the heat and electricity provided by them are thought to replace the relevant fossil-fuel inputs. Thereafter, there would still remain excess amounts of bagasse and lignin (**Table 2**), which could be utilized for co-generating additional electricity. However, this study does not consider such a possibility to simplify the arguments as far as possible. (Earlier analyses (Ueda, 2008) indicated that electricity generated in this way would be relatively small compared to biofuel productions－around 62 to 126 MJ/GJ-biofuel for sugarcane, for example. Hence the current simplified approach would not affect the results significantly.) Meanwhile, energy derived from the residues of cereal crops falls short of the demands (**Table 2**). Hence fossil fuel is thought to fill the gap.

As for biomethanol, its production generates no energy-bearing residues at all (but ashes only). Hence “biomass co-generation” is assumed to provide the required energy. Biomass co-generation in this context means that a part of biomass (i.e. sorghum or rice straw) is set aside and supplied instead to a gasification and co-generation process, where biomass is converted to fuel gas that in turn is burned in a gas turbine to generate both heat and electricity, at efficiencies of 70％ and 30％, respectively.

Secondly, the author assumes that liquid wastewater from fermentation process in bioethanol production is directly applied to farmlands. This would save the energy for treating or drying the wastewater (33％ of the total energy requirement for conversion (Wang, 1999)), but consume additional energy for transporting wastewater to farmlands (**Table 2**). The author further assumes that the nutrients contained in wastewater would save inputs of nitrogen and potassium fertilizers by 50％ after Furue and Nagata (1994).

Although some previous studies on corn bioethanol have claimed the efficacy of co-producing DDGS (distillers' dark grain with solubles) for animal feed by drying up liquid wastewater (e.g. Malça and Freire, 2006; Hill et al., 2006), this study rather emphasizes the importance of saving fossil energy input by omitting the DDGS production process. This is because the demands for DDGS are uncertain in Japan at present, and sustainability of energy crop production might be enhanced through applying nutrients in wastewater to farmlands, just as practiced widely in sugarcane fields in Brazil (Pessoa-Jr et al., 2005).

### f Methods for life cycle inventory analysis

Life cycle inventory analysis is conducted using the LCA software SimaPro 6 (PRé Consultants, the Netherlands). Collected data described above are input and the following parameters calculated with the incorporated programs shown in square brackets (Frischknecht et al., 2004):

- Fossil fuel consumption [Cumulative Energy Demand]
- Emission of greenhouse gas [IPCC 2001 GWP 20a V1.01]

Using the above results, the author further calculates several indicators as described later.

In this way, the data collected by the author are supplemented by the databases incorporated in SimaPro 6, namely ecoinvent 1.01 and Buwal 250, which enable the inclusion of materials, energy and emissions associated with the manufacture and transport of various inputs (resources) in the LCI analysis. Although the information in these databases had been accumulated mostly in West Europe, it could be assumed that the manufacturing processes for common industrial products like agrochemicals and fertilizers would be quite similar between West Europe and Japan.

## 2 Results

### a Fossil fuel consumption

Fossil fuel consumptions in producing 1 GJ of biofuels are shown in **Figs.3** (Scenario 1) and **4** (Scenario 2). In these figures, energy consumptions exceeding 1000 MJ (＝1 GJ) imply negative energy production: fossil energy input is larger than the bioenergy produced.

#### (1) Energy consumption for crop production

For the most crops examined, the indirect energy consumptions for crop cultivation (i.e. energy required to

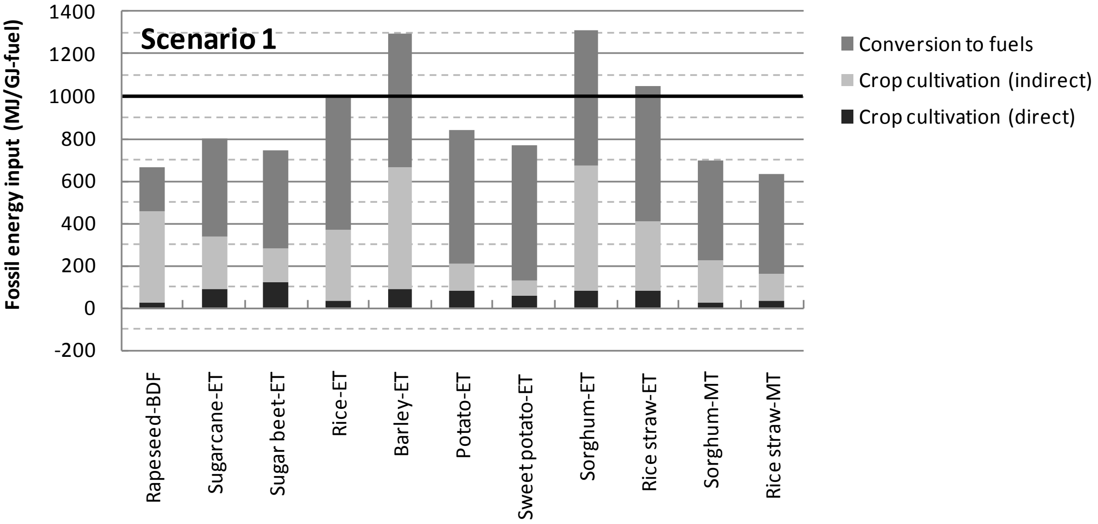

**Fig.3** Fossil fuel consumption in producing 1 GJ of biofuel (Scenario 1)
Note: BDF: biodiesel fuel, ET: bioethanol, MT: biomethanol.
Fossil energy input below 1000 MJ indicates positive bioenergy production.

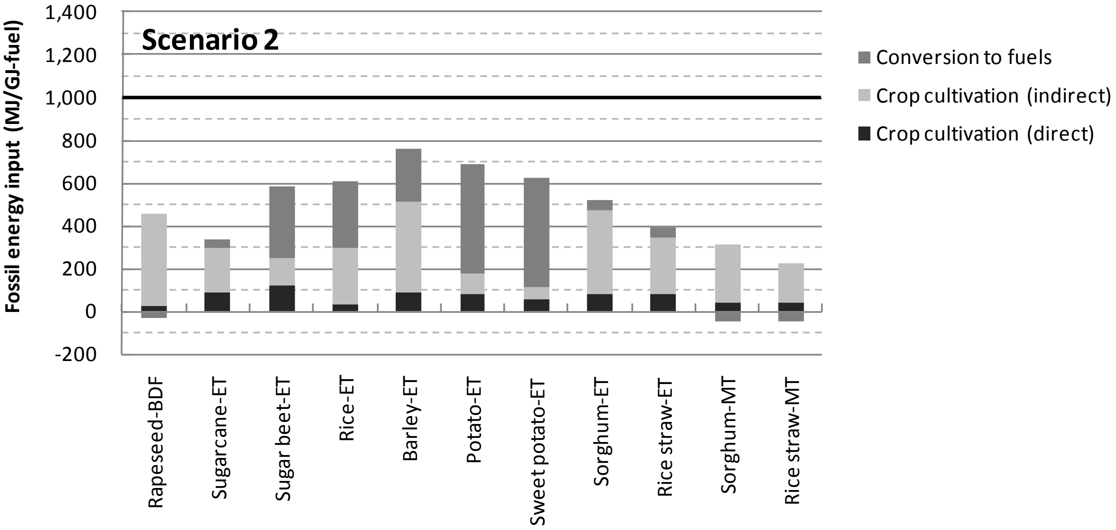

**Fig.4** Fossil fuel consumption in producing 1 GJ of biofuel (Scenario 2)

produce fertilizers, agrochemicals, seeds and fixed assets) are much larger than the direct ones (i.e. fuel consumptions for driving agricultural machinery and transporting/processing the harvests) in both scenarios. Therefore, if energy consumption for crop cultivation is to be reduced, cutting fertilizer and agrochemical inputs should first be attempted.

When comparing each crop, an important factor to affect the energy requirement is the crop yield. This is because a lower yield implies that a larger area of farmland should be cultivated in preparing feedstock for producing 1 GJ of biofuels. Hence potato and sweet potato show relatively lower energy consumptions, which are largely attributed to their higher yields (as well as the lower fertilizer inputs per ha) (**Table 1**). Similarly, a large difference between rice and barley could be explained by their difference in yields.

When comparing Scenarios 1 and 2 on bioethanol, Scenario 2 shows lower indirect energy consumptions, as it assumes to cut nitrogen and potassium fertilizers by half (**Table 2**). For biomethanol, by contrast, Scenario 2 shows larger energy requirements than Scenario 1, as additional amount of feedstock should be input into the conversion process to provide heat (“biomass co-generation”) under Scenario 2.

### (2) Energy consumption for converting biomass to bioenergy

When comparing energy consumptions for converting feedstock to biofuel in Scenario 1 (**Fig.3**), biodiesel is distinctive in its smaller energy consumption even though the conversion processes are assumed to be driven solely by fossil fuels. For the other biofuels, the energy for conversion occupies a significant share in total energy requirement.

In Scenario 2 (**Fig.4**), fossil energy consumptions are reduced compared to Scenario 1 owing to the following reasons. First, process residues substitute a part or all of the direct fossil-fuel inputs for conversion, except for sugar beet and potatoes. Second, for bioethanol, energy consumptions for drying/treating fermentation wastewater are saved through direct application of wastewater to farmlands. Thus, large differences in energy consumptions between the two scenarios would demonstrate the efficacy of strategies of Scenario 2 in saving fossil fuels in conversion processes.

### b　Net energy balance

**Fig.5** shows the net energy balance (NEB) of bioenergy production, which is defined as:

$$NEB = GP/FC \qquad (1)$$

where: *GP* is gross production of bioenergy (GJ), and *FC* is fossil fuel consumption (both direct and indirect) in producing *GP* (GJ).

In Scenario 1, NEBs for rice, barley, sorghum and rice straw (bioethanol) stay below 1.0, indicating negative energy productions. Energy consumptions for these crops are characterized by large energy requirements for crop cultivation (**Fig.3**). Thus, for cereal crops, improving the crop yields without significantly increasing fertilizers etc. would be necessary for improving the NEBs. As for ligno-cellulosic bioethanol, improving the conversion efficiency is also indispensable, as it should save feedstock inputs for conversion. Meanwhile, NEBs for the other crops are in a moderate range between 1.0 and 1.6.

In Scenario 2, NEBs are generally improved relative to Scenario 1 (**Fig.5**), and all the crops show NEBs above 1.0. In particular, the effects of replacing fossil fuels by process residues should be significant, as NEBs improve significantly for rapeseed, sugarcane and ligno-cellulosic biomass, where the entire fossil-fuel inputs for conversion are replaced by process residues. Nevertheless, wastewater application assumed in Scenario 2 contributes to small improvements in NEBs for the other crops as well.

Comparing the result of this study with recent LCA studies, NEBs of corn bioethanol in USA were reported roughly between 1.2 and 1.6 (Hammerschlag, 2006; Hill et al., 2006), which are larger than those of cereal-crop bioethanol in Scenario 1 (0.8 to 1.0), but comparable with those in Scenario 2 (1.3 to 1.7). NEBs of sugarcane

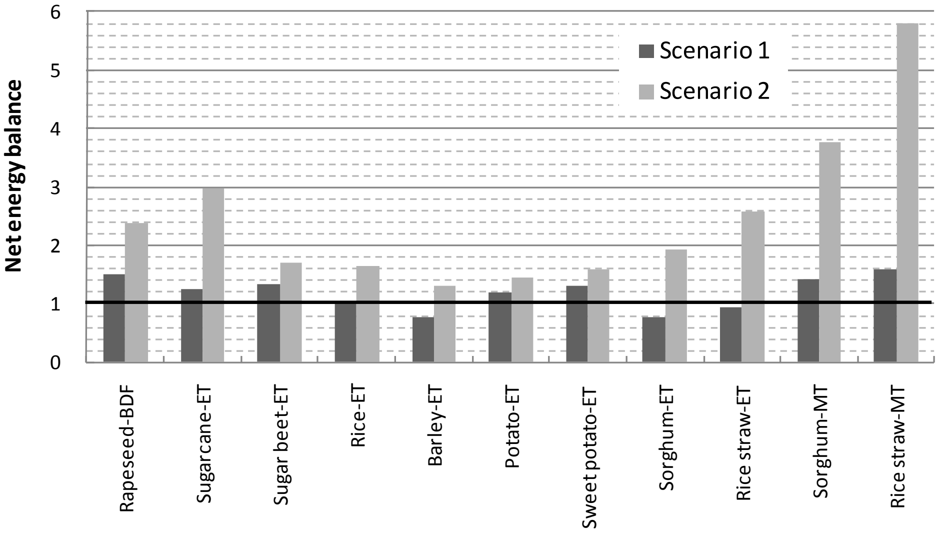

**Fig.5**　Net energy balance of biofuel production
Note: Net energy balance above one indicates positive bioenergy production.

bioethanol in Brazil were reported as 8.3 on average (IEA, 2004), which are far larger than the results of this study (1.3 to 3.0). The main reason for discrepancies in these crops would be the differences in crop yields as well as the scale of production. NEBs of ligno-cellulosic bioethanol were reported to be 4.4 to 6.6 (Hammerschlag, 2006), which are larger than those of either scenarios of this study. This would mainly be attributed to the differences in assumed conversion efficiencies.

### c　Land use efficiency

**Fig.6** shows the land use efficiency (LUE), which is the net energy production per unit area of farmland, and defined as:

$$LUE = \frac{GP - FC}{A} \tag{2}$$

where: $A$ is an area of farmland (ha) required to produce $GP$.

This indicator roughly corresponds to the crop yields. For instance, higher-yield crops like sugarcane, sugar beet, potato, sweet potato (bioethanol) and sorghum (biomethanol) show higher LUEs. On the other hand, LUEs of rice straw stay low in both scenarios, because only straw is used for generating biofuels. This implies that the feedstock must be collected from larger areas if a conversion facility is solely fed with rice straw.

### d　Greenhouse gas (GHG) emissions

Greenhouse gas (GHG) emissions associated with biofuel production are shown in **Figs.7** (Scenario 1) and **8** (Scenario 2). Here the direct emissions in crop cultivation include $N_2O$ and $CH_4$ emissions from farmland soils, in addition to the factors discussed earlier in Section II-2-a-(1). GHG emissions in burning biofuels (and process residues) are assumed to be zero according to their carbon-neutral nature. Accordingly, consuming 1 GJ of biodiesel is thought to displace emissions from consuming 1 GJ of diesel fuel (termed “avoided emission” in **Figs.7** and **8**). Likewise, both bioethanol and biomethanol would displace emissions from energy-equivalent gasoline.

Unlike energy consumptions, direct GHG emissions in crop cultivation have significant impacts for some crops, due in part to $N_2O$ and $CH_4$ emissions from farmlands (**Figs.7** and **8**). Accordingly, for bioethanol, halving of nitrogen fertilizers through wastewater recycling in Scenario 2 has effects of reducing both direct emissions ($N_2O$ from soils) and indirect ones (emissions in producing the fertilizers). Moreover, GHG emissions in the conversion processes are reduced in Scenario 2 thanks to the similar reasons as discussed in Section II-2-a-(2).

In order for biofuel productions to be meaningful in terms of GHG reduction, emissions throughout producing biofuels must be smaller than the displaced (avoided) emissions from fossil-fuel production and use. Hence **Fig.9** shows

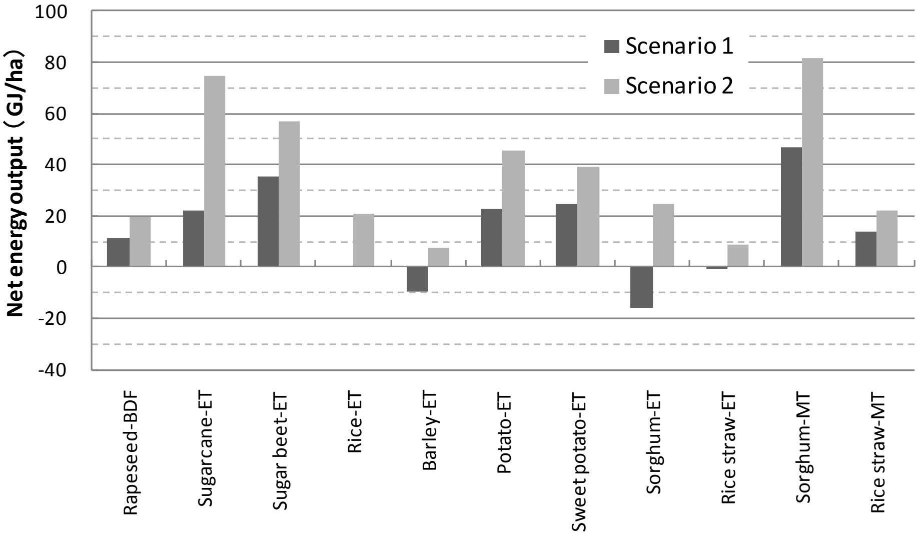

**Fig.6**　Land use efficiency of biofuel production (Net energy output per 1 ha of farmland)

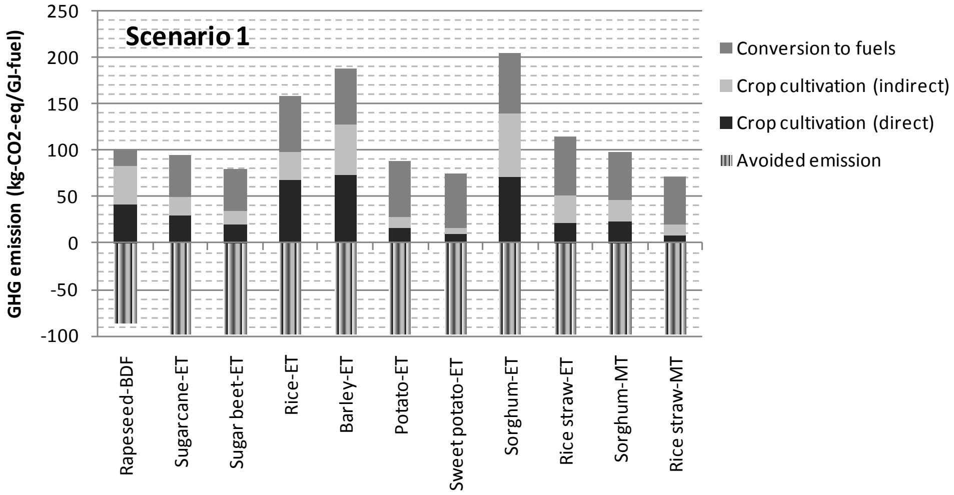

**Fig.7** Greenhouse gas emissions in producing 1GJ of biofuels (Scenario 1)

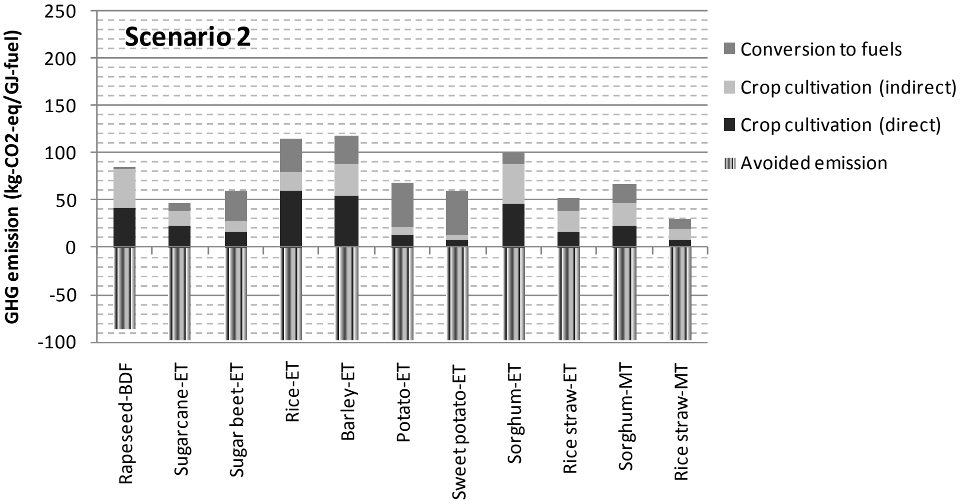

**Fig.8** Greenhouse gas emissions in producing 1GJ of biofuels (Scenario 2)

GHG emissions of biofuels relative to those of fossil fuels, which is defined as:

$$R = \frac{GGE}{AGG} \times 100 \qquad (3)$$

where: *R* is the relative GHG emission (% ), *GGE* is the emission in producing 1 GJ of bioenergy (kg-$CO_2$-eq.), and *AGG* is the emission in producing and burning 1 GJ of diesel fuel or gasoline (kg-$CO_2$-eq.) (i.e. avoided emission by using 1 GJ of bioenergy).

In general, Scenario 2 shows smaller emissions compared to Scenario 1 (**Fig.9**). Nevertheless, emissions of rice, barley and sorghum (bioethanol) still exceed 100 % relative to fossil fuels. Therefore, some improvements (e.g. increasing crop yields) should be attempted before those kinds of biofuels become viable in terms of GHG reduction. On the other hand, sugarcane, sugar beet, potato, sweet potato, rice straw (bioethanol), as well as sorghum and rice straw (biomethanol), show significant reductions in GHG emission in Scenario 2. Hence those crops should be recommended from the viewpoint of GHG reduction.

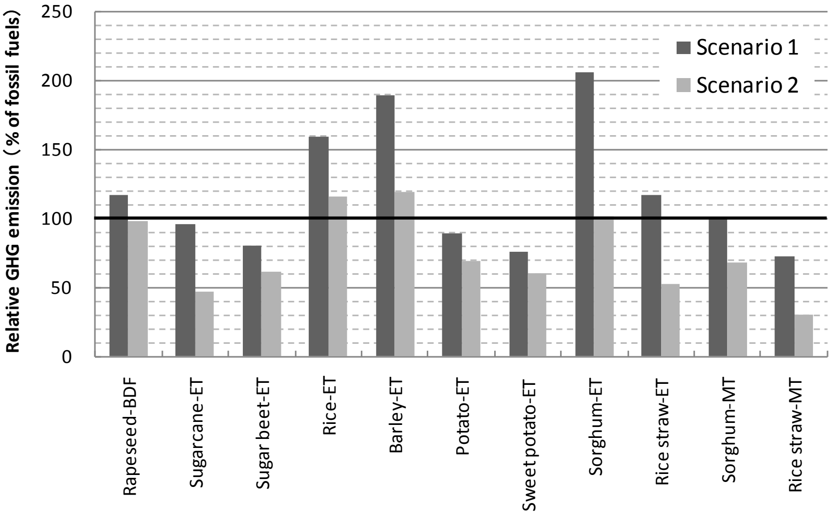

**Fig.9** Greenhouse gas emissions of biofuels relative to fossil fuels
Note: Relative GHG emission below 100% indicates positive GHG reduction.

## III Cost analysis

### 1 Methodology

#### a Crop production costs

Data on crop production costs (**Table 3**) are mostly collected from statistical databases of the Ministry of Agriculture, Forestry and Fisheries (MAFF) of Japan (MAFF, 2010). The cost includes those for variable inputs (seeds, fertilizer, chemicals, fossil fuels etc.), fixed capital (agricultural machinery, farm building, irrigation facilities etc.), as well as labor, interests and rents. Data on rapeseed were obtained from other local sources, as the MAFF did not offer them. It should be noted that the above data refer to the costs (mostly in 2005) for producing food or fodder crops, and therefore do not directly indicate the costs for energy crops. Nevertheless, analyses based on these data should provide a reference for future discussions on cost reduction in cultivating energy crops.

Data on costs for supplying rice straw are drawn from JARUS (2010). The figure is the average of three pilot studies in Japan, and includes costs for straw collection in fields, transportation and storage. Although the original data did not include fixed costs, the author estimated and added them referring to data of fodder crop production (MAFF, 2010).

#### b Energy conversion costs

Cost data for conversion processes were obtained from the following sources: CNRE (2005) for biodiesel (at an annual production of 550kL/y); NFACA (2006) for bioethanol from starch crops (35,700kL/y); and Kobayashi et al. (2005) for biomethanol (37,900kL/y). For biodiesel, the author employed a cost at relatively small-scale production, because such a scale had been predominant for biodiesel in Japan. Conversion costs of bioethanol from sugar crops were assumed to be 71％ of that from starch crops, according to a hearing from experts at National Food Research Institute in Tsukuba, Japan. Conversion costs of ligno-cellulosic bioethanol are not included in **Table 3**, because current technologies are too primitive to obtain any plausible point estimate. The author omits costs for transporting biofuels to supply stations, profit margin of biofuel producers, as well as possible taxes imposed on biofuels.

### 2 Results

Total costs of biofuel production are estimated at 633Yen/L-DE (Diesel Equivalent) for biodiesel and 223 to 773 Yen/L-GE (Gasoline Equivalent) for bioethanol, and 136 to 263 Yen/L-GE for biomethanol (**Table 3**). These figures are dominated by crop production costs, and are significantly higher than current fossil fuel prices in Japan. Nevertheless, the costs are relatively smaller for potato, sugar beet (bioethanol), as well as sorghum and rice straw (biomethanol). In any crops, however, significant efforts are required in cost reduction, before biofuels become competitive with fossil fuels.

For ligno-cellulosic bioethanol, a simple sensitivity analysis is provided in **Fig.10**: given the assumed feedstock production costs, the effect of varying conversion costs is depicted against the total cost. It is implied that bioethanol from rice straw may become competitive with gasoline (tax included), provided that the conversion cost is reduced roughly in the same range as that for sugar/starch bioethanol.

**Table 3** Estimated costs of biofuel production in Japan

| | Unit | Rapeseed | Sugarcane | Sugar beet | Rice | Barley | Potato | Sweet potato | Sorghum | Rice straw | Sorghum | Rice straw |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Biofuels[a] | | BDF | ET (sugar) | | ET (starch) | | | | ET (ligno-cellulosic) | | MT | |
| **Costs per kg of produce[b]** | | | | | | | | | | | | |
| Crop production cost | Yen/kg | 235 | 28 | 15 | 210 | 199 | 16 | 50 | 37 | 9 | 37 | 9 |
| **Costs per liter (fossil-fuel equivalent) of biofuel[c]** | | | | | | | | | | | | |
| Crop production cost | Yen/L | 547 | 526 | 243 | 719 | 661 | 169 | 406 | 377 | 91 | 176 | 49 |
| Energy conversion cost | Yen/L | 87 | 38 | 38 | 54 | 54 | 54 | 54 | − | − | 87 | 87 |
| Total cost | Yen/L | 633 | 564 | 281 | 773 | 715 | 223 | 460 | − | − | 263 | 136 |
| Total cost | $/L[d] | 7.45 | 6.64 | 3.31 | 9.09 | 8.42 | 2.62 | 5.41 | − | − | 3.10 | 1.60 |
| **Ratio to fossil fuel price[e]** | | | | | | | | | | | | |
| (taxes on fossil fuels excluded) | | 10.63 | 9.49 | 4.73 | 12.99 | 12.02 | 3.74 | 7.73 | − | − | 4.43 | 2.29 |
| (taxes on fossil fuels included) | | 5.73 | 4.30 | 2.14 | 5.88 | 5.44 | 1.70 | 3.50 | − | − | 2.00 | 1.04 |

**Notes**:

[a] BDF: biodiesel fuel, ET: bioethanol, MT: biomethanol.

[b] Original data were shown in costs per ha of farmland (excluding rice straw). They are converted to the costs per kg of produce using the crop yields in Table 1.

[c] Costs per diesel-equivalent liter for biodiesel; and costs per gasoline-equivalent liter for bioethanol and biomethanol.

[d] Exchange rate: 85 yen/$.

[e] Ratio to diesel fuel for biodiesel; ratio to gasoline for bioethanol and biomethanol. Fossil fuel prices are the national averages between Sep. 2009 and Aug. 2010 (OIC, 2010): [Diesel fuel] 59.6 (tax excluded) or 110.6 Yen/L (tax included); [Gasoline] 59.5 (tax excluded) or 131.4 Yen/L (tax included).

**Main data sources** (for more details, see text and Ueda (2008)):

－Crop production cost: [Rapeseed] Yokohama Town Council (2001); [The other energy crops] MAFF (2010); [Rice straw] JARUS (2010).

－Energy conversion cost: [Biodiesel] CNRE (2005); [Sugar/starch bioethanol] NFACA (2006); [Biomethanol] Kobayashi et al. (2005).

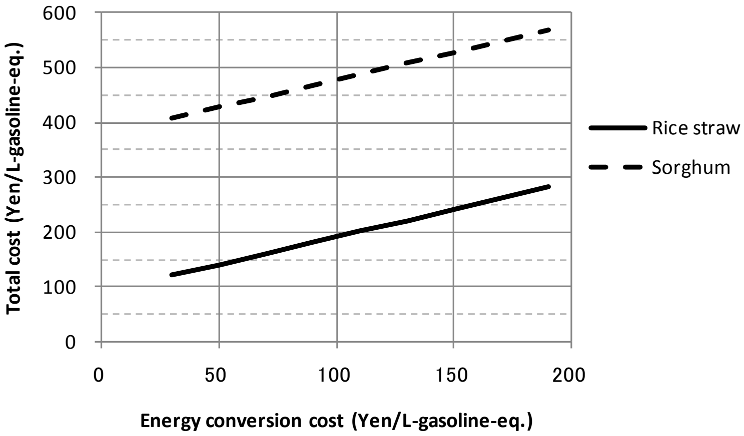

**Fig.10** Relationship between the energy conversion cost and the total cost for ligno-cellulosic bioethanol
Note: Feedstock production costs are drawn from **Table 3**.

## IV Biofuel production potentials across Japan

### 1 Scenarios

Among biofuel conversion processes analyzed, biodiesel suffers lower land use efficiency compared to some of bioethanol and biomethanol (**Fig.6**). This would discourage their large-scale applications using dedicated crop (i.e. rapeseed) in Japan, where land resources are rather scarce. (Alternatively, however, small-scale biodiesel productions from waste cook oil as a main feedstock are becoming increasingly popular across Japan.)

Next, comparing bioethanol and biomethanol, biomethanol shows some advantages in terms of net energy balance, land use efficiency and production costs (**Figs.5** and **6**; **Table 3**). However, as the Japanese government is currently focusing on bioethanol for supplementing gasoline, it would be rather difficult to establish fuel distribution infrastructure for biomethanol in addition to that for bioethanol. Besides, biomethanol is currently not favored as a gasoline alternative because of the lower energy content and possible toxicity (IEA, 2004). (Alternatively, however, biomethanol may find other demands like fuel cells and additives for biodiesel production in the near future.)

Thus, the following discussion focuses on a strategy for replacing gasoline with bioethanol by employing domestic biomass in Japan at a large scale. The discussions and calculations of relevant parameters are based on the conditions of Scenario 2 (**Table 2**) discussed previously.

#### a Energy crops on fallow lands

For many years, Japan has suffered from low food self-sufficiency, which decreased to around 40％ (on a calorie basis) in 2005. Therefore, converting farmlands for food/fodder crops to those for energy crops would be discouraged in view of food security. Thus, we will discuss below about an option of cultivating energy crops on fallow farmlands, which amount to 385,800ha across Japan in 2005.

Among the energy crops for bioethanol, sugarcane attained the best figures on net energy balance, land use efficiency and GHG reduction (**Figs.5**, **6** and **9**). Sugar beet, potato and sweet potato showed the second-best performances in terms of land use efficiency and GHG reduction (**Figs.6** and **9**). In terms of production costs, potato offers the cheapest option, followed by sugar beet, sweet potato and sugarcane (**Table 3**). By contrast, results of rice, barley and sorghum (bioethanol) are rather disappointing, especially in terms of GHG reduction and costs (**Fig.9** and **Table 3**). Therefore, potato is selected as the main crop to be cultivated on fallow lands, supplemented by sweet potato and sugarcane in southern, warmer regions of Kyushu and Okinawa (**Table 4**).

#### b Crop residues

Rice is the predominant cereal crop in Japan, occupying over 90％ of the total cereal crop production on a value basis. Therefore, the author focuses on rice straw among various crop residues generated. MAFF (2005) estimated that around 20％ of rice straw is currently utilized for compost production, animal feed or bedding materials for livestock, while the remaining 80％ is underutilized (mostly burned or plowed back to fields). Thus, this study assumes that 80％ of rice straw that is generated on all the paddy fields across Japan is collected and converted to bioethanol. It should be noted, however, realizing this potential requires the commercialization of second-generation (ligno-cellulosic) bioethanol. Compensation of nutrients taken from fields with the straw had already been taken into account when setting the system boundary of the LCA (see Section II-1-c).

**Table 4**　Estimated potentials of bioethanol production in Japan

| | Region | Area [b] | Feedstock | Gross production | Net production [c] | GHG reduction |
|---|---|---|---|---|---|---|
| | | ha | | kL/y | kL/y | t -$CO_2$/ y |
| Energy crops in fallow farmlands | Hokkaido, Honshu & Shikoku | 321,661 | Potato | 1,348,802 | 422,175 | 1,423,391 |
| | Kyushu | 60,899 | Sweet potato | 184,005 | 69,370 | 247,023 |
| | Okinawa | 3,240 | Sugarcane | 10,505 | 6,986 | 19,046 |
| Total of energy crops | | 385,800 | | 1,543,312 | 498,531 | 1,689,460 |
| (％ of national gasoline consumption or GHG emission) [a] | | | | 2.61 | 0.84 | 0.13 |
| Residue from all paddy fields in Japan | | 1,864,714 | Rice straw | 770,430 | 470,733 | 1,260,870 |
| Total of energy crops and rice straw | | | | 2,313,742 | 969,263 | 2,950,330 |
| (％ of national gasoline consumption or GHG emission) [a] | | | | 3.89 | 1.62 | 0.23 |

**Notes:**

The potentials are calculated on the basis of Scenario 2 in text.

[a] Gasoline consumption is the national sum in 2007 (MIAC, 2010); GHG emission in 1990 (MOE, 2005).

[b] Census of Agriculture and Forestry 2005 (MAFF, 2010).

[c] (Gross production) – (Fossil energy input for producing the gross production).

## 2　Estimated potentials

As a national total of energy crops on fallow lands, gross bioethanol production would amount to 2.6％ of national gasoline consumption in 2007 (MIAC, 2010), but net production (i.e. gross production minus energy requirement in biofuel production) remains 0.8％ (**Table 4**). If the potential from rice straw is included, the gross and net productions would increase to 3.9 and 1.6％, respectively. The corresponding gross production of 2.31 million kL-GE (gasoline eq.)/year is smaller than the long-term projection of MAFF (2007), which estimated 2.6 to 2.8 million kL-GE/year could be produced in 2030 using energy crops on fallow lands and crop residues. The discrepancy would probably come from the differences in assumed crop yields and conversion efficiencies.

In producing the above sum (2.31 million kL-GE/year) of bioethanol, total net GHG reduction potential is estimated to be 3,078 thousand ton-$CO_2$-eq/year, which comprises of: 1,689 thousand ton from energy crops and 1,389 thousand ton from rice straw. The total reduction potential corresponds with 0.23％ of Japan's national GHG emission in 1990 (MOE, 2005). On the other hand, the Kyoto Protocol demands Japan to cut the GHG emission by 6％ compared to that in 1990. The reduction potential from biofuel production would therefore be worth considering as Japan is struggling to meet the obligation of the Protocol, although the costs of such reduction should first be compared with other options such as promoting solar cells.

## V　Discussions and conclusions

This study has demonstrated the potential of domestic biofuels in contributing to national strategies of cutting fossil fuel consumptions and related GHG emissions in Japan to some extent. Using energy crops on fallow lands and rice straw across Japan, the net production potential of bioethanol were estimated as 1.62％ of national gasoline consumption in 2007, and the relevant GHG reduction potential as 0.23％ of national emission in 1990 (**Table 4**).

Nonetheless, realizing such a potential would face two major barriers to overcome. First, for the most crops studied, implementing Scenario 2 would be necessary for achieving significant results in positive net energy production (**Figs.5** and **6**) and GHG reduction (**Fig.9**). These strongly suggest the importance of saving fossil fuel input by exploiting heat from combusting crop residues and by directly applying fermentation wastewater to farmlands. However, effects of applying such wastewater remain controversial. On the positive side, Furue and Nagata (1994) demonstrated that wastewater from spirit (*shochu*) production process could be applied to sugarcane farms, provided that it was done well before plantation, since such wastewater released nitrogen only slowly. On the negative side, Chen and Shinogi (2010) applied ethanol-fermentation wastewater (that used final molasses from sugarcane refinery as raw material) to farm soils, and suggested negative impacts on nitrogen availability and soil physics (such as reduction in soil permeability). Kamimura et al. (1993) similarly suggested that direct application of fermentation wastewater might inhibit growth of vegetables because of the nutrient imbalances contained in wastewater. This study followed the results of Furue and Nagata (1994), and simply assumed to recycle wastewater directly to farmlands used to provide each feedstock, and the whole amount of wastewater could safely be applied. Nevertheless, the mixed results of previous studies imply that efficacy or safety of such application may depend on the type of crops, soils and wastewater, as well as the methods of application. These issues have not been thoroughly examined in Japan, and hence are left to future studies.

Second, the production costs of biofuels are significantly higher than those of fossil fuels (**Table 3**). As for ligno-cellulosic bioethanol, reducing the conversion costs would be indispensable before it becomes economically viable (**Fig.10**). This is essentially a matter of increasing the conversion efficiency, because doing so should save expensive inputs such as enzyme and yeast. Nevertheless, this has been a major challenge in research and development for decades, which therefore requires a lot more efforts to overcome. As for the other biofuels, there would not be much room to cut the conversion costs, as the relevant technologies are already matured. Hence reducing crop production costs would be essential. This would be achieved, above all, by increasing the crop yields without significantly increasing fertilizer inputs. This is another big challenge which calls for developments in new crop varieties as well as cultivation technologies.

Finally, we discuss the limitations of this study, and hence the directions for future research. First, this study focused on biofuel production processes, and hence the role of crop residues was limited to energy supplements. Nevertheless, the whole system of biofuel production could become more cost-effective by integrating co-production processes. For instance, research institutes across Japan are investigating to exploit process residues (such as beet pulp) for co-producing industrial chemicals (such as cosmetics) alongside biofuels (Ueda, 2006). Involving such results in cost analyses will be left to future studies. Second, this study confined analyses on liquid biofuels only. Nonetheless, several pilot studies in Japan suggested the importance of integrating different kinds of bioenergy production processes, including methane fermentation and pyrolysis, in order to fully exploit various kinds of biomass generated in Japanese rural areas (e.g. Yuyama et al., 2010; Shinogi and Kameyama, 2007), where various types of agriculture and forestry, rather than a large-scale monoculture, are concurrently conducted. Undertaking LCA and cost analyses on such an integrated system will be another challenging issue.

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# 国産農業バイオマスを用いたバイオ燃料生産の可能性

上田達己

## 要　旨

世界各地では，化石燃料依存からの脱却，地球温暖化防止への貢献，農村における雇用の拡大などを目的として，近年大規模なバイオ燃料の生産が拡大しているが，それに伴う熱帯雨林の破壊，土地･水資源の逼迫などが懸念されている。一方で，我が国は，耕作放棄地や未利用バイオマスを活用した，土地利用の改変を伴わないバイオ燃料生産拡大の可能性を有している。そこで本研究は，国産バイオマスを用いたバイオ燃料生産について，ライフサイクルアセスメントとコスト分析を行い，さらに全国的にみた生産ポテンシャルを概観する。結果として，以下の点が明らかとなった。①エネルギー収支，土地利用効率および温室効果ガス削減の観点からは，おおむねサトウキビ・テンサイ・イモ類(バイオエタノール)，ソルガム・稲わら（バイオメタノール）が高く評価された。②生産費の点からは，バイオメタノールおよびジャガイモ・テンサイのバイオエタノールが比較的商用生産への距離が近いとみられた。しかしながら，化石燃料と同等の生産費を実現するには，さらなる作物栽培費の低減が必要である。③作物残渣・リグニンを代替エネルギーとして活用すること，および発酵廃液の農地還元をシステムに組み込むことが，エネルギー収支などの向上を図るうえで重要である。④耕作放棄地へのイモ類・サトウキビの作付けおよび全国の水田からの稲わらの収集により，バイオエタノールの純生産ポテンシャルは全国のガソリン消費量（2007年）の1.62%，また温室効果ガス削減ポテンシャルは全国排出量（1990年）の0.23%であると試算された。

**キーワード**：農業系残渣，バイオエネルギー，バイオエタノール，バイオマス，LCA